RADIOACTIVITIES IN RETURNED LUNAR MATERIALS

Semiannual Progress Report No. 3

For the period 1 February 1972 through 31 July 1972

Grant NGR 09-015-145

August 1972

Prepared for

National Aeronautics and Space Administration
Manned Spacecraft Center
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ABSTRACT

The Ar^{37}, Ar^{39}, and H^3 were measured at four depths (from 0 to 19.5 cm) of the deep core from Apollo 16 and in four other Apollo 16 samples. The Ar^{37} increased steadily from 40 dpm/kg at the top of the core to 68 dpm/kg at 19-cm depth. The comparison of the Ar^{37} in the core with that in rock 15555 shows that the solar flare at the time of the Apollo 16 mission was approximately an order of magnitude less intense than solar flares of 24 January 1971 and 2 November 1969, which occurred before the Apollo 14 and 12 missions.

The Ar^{39} activities in the top 19 cm of the deep core varied little with depth. Because the Apollo 16 samples have a much higher Ca content and much lower Fe and Ti contents than do the documented rocks from previous missions, the Ar^{39} in the Fe, Ca, and K can be determined from Ar^{39} measurements on lunar material if a Ti cross section is assumed. For a reasonable Ti cross section, the Ar^{39} activity in Fe (20 dpm/kg) gives an estimate of the intensity of solar flares during the past 1000 years. The energetic solar proton flux (> 300 Mev) averaged over the past 1000 years from the Ar^{39} in Fe is $3 \times 10^7/cm^2$ yr. This is approximately a factor of 3 smaller than the flare intensities observed during the high years of 1956, 1959, and 1960 and indicates that such high years were quite common. The solar-flare proton flux (>~50 Mev) averaged over the past 1000 years could be obtained from Ar^{39} in Ca, if appropriate cross sections were measured.

The tritium in the deep-core samples decreased from 430 ± 25 dpm/kg at 0- to 1.5-cm depth to 250 ± 15 dpm/kg at 10- to 11.5-cm depth and then was relatively constant at greater depths. The depth behavior of the tritium in the soil is similar to that in documented rocks; however, the tritium contents of the soils are nearly a factor of 2 higher than those in some rock samples at equivalent depths.

RADIOACTIVITIES IN RETURNED LUNAR MATERIALS

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E. L. Fireman

1. INTRODUCTION

A collaborative study of the H^3, Ar^{37}, and Ar^{39} in the Apollo 16 deep core with R. Davis and R. Stoenner of Brookhaven National Laboratory was undertaken. We received and analyzed samples from the top section to study solar flares; they received samples from the bottom sections to investigate galactic cosmic rays. The results from both groups should eventually be combined to give the detailed behavior of the three radioactivities for the entire length of the deep core. In this report, we only discuss our results. Our findings at this time are preliminary, since the chemical compositions of our core samples have only been estimated from other Apollo 16 soils and because further counting should reduce the errors.

A solar flare was reported to have occurred 1 or 2 days before the Apollo 16 samples were recovered. In order to be able to study this flare quickly, we received only a few days after the Apollo 16 samples were returned two soil samples taken from different depths in a trench. We later received four core samples and two soil samples from other locations.

2. SAMPLE DESCRIPTION

Samples 60007, 93, 60007, 94, and 60007, 95 were taken from 0- to 1.5-cm depth in the core; the weights of these three samples totaled 2.08 g. Samples 60007, 99, 60007, 100, and 60007, 101 were taken from 10.0- to 11.5-cm depth in the core; their weights totaled 2.07 g. Samples 60007, 102, 60007, 103, and 60007, 104 were from 18.0- to 19.5-cm in the core; their weights totaled 2.07 g. The three samples from the same depth were combined for Ar^{37}, Ar^{39}, and H^3 analysis. The combined

samples are designated as *60007, 93, 94, 95*; *60007, 96, 97, 98*; *60007, 99, 100, 101*; and 60007, 102, 103, 104 in our tables. According to Dr. N. Hubbard (private communication, 1972), the Apollo 16 soil samples have high Ca contents, 11.0 to 12.0% by weight; low Fe and Ti contents, 3.5 to 4.5%, and, 0.27 to 0.40%, respectively; and K contents between 0.075 and 0.085%. The soil samples that Dr. N. Hubbard analyzed were from shallow depths, 0 to 20 cm, and are uniform in chemical composition within 10%. We have, therefore, assigned a similar chemical composition (given in Table 2) to our 60007 samples. Dr. R. Stoenner analyzed the Ca content of samples from deeper locations in the core and obtained Ca contents that range from 11.5 to 14.2%. His Ca variation is somewhat larger than that obtained by Dr. N. Hubbard; however, the measured Ca contents agree within 20%.

The description of the Apollo 16 samples and the manner of their collection are given in Astrogeology 51, a report by the U.S.G.S. and distributed by the Manned Spacecraft Center in Houston. According to this report, sample 61241 was scooped near the top of a trench dug at the edge of Plum Crater and 61220 was scooped from near the bottom of the same trench. We received a 2.08-g sample of 61241 called 61241, 1 and a 2.07 g sample of 61220 called 61220, 1. Sample 63501 was soil scooped near the surface at station 13 and passed through a 1-mm sieve. Sample 63321 was soil scooped from the permanent shadow of a large rock – Shadow Rock – at Station 13. We analyzed a 3.1-g sample of 63501, 19 and a 3.0-g sample 63321, 5.

3. RESULTS

Our experimental procedures are unchanged from those described in our previous publications (Fireman et al., 1970; D'Amico et al., 1970, 1971). Table 1 gives the Ar^{37} results for our Apollo 16 samples, corrected to 21 April 1972 as the collection date, together with depths, Ca contents obtained from other experiments, and selected Ar^{37} results from previous missions. The Ar^{37} activity in the core increased with increasing depth. At 0- to 1.5-cm depth (0 to 2.1 g/cm^2), there were 39.0 ± 2.8 dpm/kg; at 3.5- to 5.0-cm depth (5.0 to 7.1 g/cm^2), 47.9 ± 1.9 dpm/kg; at 10.0- to 11.5-cm depth (14.0 to 16.1 g/cm^2), 58.5 ± 2.4 dpm/kg; and at 18.0- to 19.5-cm depth, 68.1 ± 2.9 dpm/kg of Ar^{37}. The ratio Ar^{37}/Ca increased from 325 ± 22 to 567 ± 24 dpm/kg Ca. If these Ar^{37} results are compared with the Ar^{37} measurements in 15555 (Fireman

et al., 1972), a documented rock not subjected to any solar flare, it is seen that the Ar^{37} in both materials increased with depth. From this comparison of Apollo 15 and 16 materials, it appears that the 19 April 1972 flare was a minor event quite unlike the 24 January 1971 one, which caused a much larger increase in the Ar^{37} activities at shallow depths and made the Ar^{37} activities in rocks 14321 decrease with increasing depth. The comparison of the Ar^{37}/Ca ratio in the top 2 g/cm^2 of 15555 with that in the top of core 60007 shows a difference in Ar^{37}/Ca of only 90 ± 50 dpm/kg Ca. The 24 January 1971 flare caused an increase of 396 ± 58 dpm/kg Ca in the top 2 g/cm^2 of 14321 at the time of recovery. Two weeks elapsed between the 24 January 1971 flare and the recovery of rock 14321, so that this flare caused an increase in Ar^{37}/Ca of 530 ± 80 dpm/kg Ca. The 19 April 1972 flare at the time of the Apollo 16 mission was a factor of 6 smaller than the 24 January 1971 flare. The Ar^{37}/Ca at a depth of 15 g/cm^2 in core 60007, 487 ± 20 dpm/kg Ca, agrees well with the 465 ± 47 dpm/kg Ca at the same depth in rock 15555. The Ar^{37} in both samples is produced solely by galactic cosmic rays. At a depth between 2.5 to 9.0 g/cm^2 in rock 12002, the Ar^{37}/Ca is 463 ± 28 dpm/kg, which is slightly higher than the 400 ± 16 dpm/kg Ca at depths between 5.0 to 7.1 g/cm^2 in 60007. The 2 November 1969 flare probably produced Ar^{37} at a depth of 5 g/cm^2 in rock 12002.

The depth in the moon at which galactic production of Ar^{37} is a maximum would be interesting to obtain experimentally, since it has been theoretically evaluated. The comparison of the Ar^{37} activities in the bottom samples of 60007 and 15555 indicates that this maximum is between 27 and 40 g/cm^2; a more precise location of this maximum should become available when our results on the deep core are combined with those of Drs. R. Davis and R. W. Stoenner.

The comparison of the Ar^{37} activities in samples 63501, 19, 61241, 1, and 61220, 1 with those of 60007 gives the average depths of these soil samples. The 47.2 ± 2.5 dpm/kg activity in 63501, 19 indicates its average depth to be 6.0 cm; the 43.5 ± 2.2 dpm/kg activity in 61241, 1 indicates its average depth to be 5.0 cm; and the 58.0 ± 6.0 dpm/kg activity in 61220, 1 indicates its average depth to be 11 cm.

From Ar^{37} measurements in 14321, 12002, and 15555 rocks, Fireman et al. (1972) obtained $(5.9 \pm 1.0) \times 10^6/cm^2 sr$ and $(5.1 \pm 1.2) \times 10^6/cm^2 sr$ for the solar proton fluxes above 50 Mev for the 24 January 1971 and 2 November 1969 flares, respectively. These results agree within 50% with measurements obtained with electronic detectors aboard spaceprobes and satellites. What can be said about ancient solar flares from longer-lived activities in lunar material? Other experimenters have found from a comparison of the Al^{26} (0.84×10^6 yr halflife) and the Na^{22} (2.6-yr halflife) depth dependences that the solar-flare proton fluxes (> 10 Mev) integrated over 2×10^6 yr and 6 yr were similar. The Ar^{39} (270-yr halflife) contains information about the very energetic solar flares (> 300 Mev), the flares of intermediate energy (> 50 Mev), and neutron fluxes during the past 1000 yr. One thousand years is an interesting time span because sun spots have been recorded for about 1/3 of this time, and there are conflicting data about secular solar cycles from C14 measurements in tree rings.

Four target elements, Fe, Ti, Ca, and K, when present in sufficient abundance, are important for Ar^{39} production. According to preliminary cross-section estimates, Ar^{39} can be produced in Fe and Ti only by high-energy protons (> 300 Mev), and the Ti cross section is 4 times the Fe cross section. Ar^{39} is thought to be produced in Ca by (~10-Mev) energetic neutrons and in K by neutrons of ≤ 1 Mev energy. In order to unfold the information contained in the Ar^{39} data, four samples with different chemical compositions at the same depth are needed.

Table 2 gives the measured Ar^{39} activities, the sample depths, and the Fe, Ti, Ca, and K abundances for Apollo 12, 14, 15, and 16 samples. The elements' abundances for Apollo 16 were obtained from estimates by Dr. N. Hubbard; for the other Apollo missions, the abundances were taken from various publications of the chemical composition of lunar material.

Ar^{39} data are available for four samples at the same depth with different chemical compositions (at 0 to 2 g/cm^2 and at 14 to 16 g/cm^2). A set of four simultaneous equations can be solved for the four unknowns: ($Fe \rightarrow Ar^{39}$), ($Ti \rightarrow Ar^{39}$), ($Ca \rightarrow Ar^{39}$), and ($K \rightarrow Ar^{39}$). When the calculation is done, the uncertainties are so large that no significant conclusion about solar flares during the past 1000 years can be drawn. If, however, the relative Ar^{39} production rates in Fe and Ti are assumed to be a fixed

value – for example, $\sigma_{Ar^{39}}(Ti) = 4\sigma_{Ar^{39}}(Fe)$ – then significant conclusions about solar flares during the past 1000 years can be obtained from the Ar^{39} data. It is important to measure the cross sections for Ar^{39} production from Ti with proton bombardments between 50 and 600 Mev. With the assumption that $\sigma_{Ar^{39}}(Ti) = 4\sigma_{Ar^{39}}(Fe)$, the Fe → Ar^{39} is 20 ± 4 dpm/kg Fe and is independent of depth from 0 to ~30 g/cm^2; the Ca → Ar^{39} decreases from 60 ± 7 dpm/kg Ca at 1 g/cm^2 to 35 ± 7 dpm/kg Ca at 15 g/cm^2 and then increases to 62 ± 12 dpm/kg Ca at 30 g/cm depth; and the K → Ar^{39} increases continuously from 700 ± 200 dpm/kg at 1 g/cm^2 to 2200 ± 300 dpm/kg at 30 g/cm^2 depth. By fractional dissolution of Apollo 11 samples, Begemann et al. (1970) found that (K → Ar^{39}) ~ 3000 dpm/kg K. If their Apollo 11 samples came from a depth of 15 g/cm^2, there is reasonable accord with our results. Table 2 gives the Ar^{39} activities and the calculated Ar^{39} contributions from the target elements. The Fe → Ar^{39} is two times the value expected from galactic cosmic-ray production (Reedy and Arnold, 1972), which leads to the conclusion that (> 300 Mev) protons from solar flares were as intense as the (> 300 Mev) protons from galactic cosmic rays during the past 1000 years. This conclusion depends crucially on the assumed Ti cross section. If the Ti cross section for ~300-Mev protons were 10 times the Fe cross section, then the intensity of energetic solar flares would be substantially reduced. The Ca → Ar^{39} values deduced from the Ar^{39} data decrease with increasing depth from 0 to 15 g/cm^2. Both in the Fe and in the Ca, we have evidence for solar-flare production of Ar^{39} averaged over the past 1000 years. In Fe, the evidence is for energetic solar protons (> 300 Mev); in Ca, for lower energy solar protons. The 19th solar cycle and particularly the years 1956, 1959, and 1960 were the most active in the past 20 years. Did years of similar solar activity occur frequently during the past 1000 years?

During the high years of 1956, 1959, and 1960, the average number of protons of > 300-Mev energy from solar flares, according to More and Tiffany (1962), was 3 times greater than from galactic cosmic rays, which is 4×10^7/cm^2 yr near the earth. From the fact that the Ar^{39} in Fe is twice the value expected from galactic cosmic rays, we conclude that the solar-flare (> 300 Mev) intensity averaged over the past 1000 years was equal to the intensity of galactic cosmic rays. We conclude that years when the solar-flare activity was similar to that observed in 1956, 1959, and 1960 were not rare. During the past 1000 years, approximately one-third of the years were of similarly high activity. In other words, the 19th solar cycle was fairly typical of the solar cycles during the past 1000 years. Quantitative conclusions about the solar flares

from the Ar^{39} in Ca are difficult to obtain because of uncertainties in the production cross sections. However, the depth dependence of $Ca \rightarrow Ar^{39}$ is quite different than that expected from galactic cosmic rays.

Table 3 gives the H^3 results for the Apollo 16 samples and their weights and depths. Only a small amount of tritium (between 5 and 15%) of the total was released by heating samples 61220, 1, 6124, 1, 63501, 19, and 63321, 5 at 275°C for several hours. There is no evidence for contamination by terrestrial H^3 in any of these samples. Böschler et al. (1971) found evidence for H^3 contamination in Apollo 11 samples. The core samples were melted directly without the 275°C preheat. All samples were remelted to check whether any tritium remained in the sample or in the line. Less than 10% of the total tritium was observed in the remeltings. The tritium contents of the deep core tube samples in dpm/kg were: 430 ± 25 at 0- to 1.5-cm depth, 300 ± 20 at 3.5- to 5.0-cm depth, 250 ± 15 at 10.0- to 11.5-cm depth, and 280 ± 20 at 18.0- to 19.5-cm depth. The tritium that decreased with depth from the surface reached a minimum at a depth of 15 g/cm^2 and then increased to a slightly higher value at a depth of 25 g/cm^2. This depth behavior is similar to that observed in the documented rocks from previous missions and is evidence for the production of tritium by solar flares during the past 40 yr. The H^3 activities in the Apollo 16 soil samples are, however, higher than those observed at corresponding depths in documented rocks from previous missions. There was previous evidence that the tritium contents of the Apollo 11 soils were higher than those of the Apollo 11 rocks (Fireman et al., 1970; Stoenner et al., 1970a, b).

The tritium contents of the other Apollo 16 soil samples (not from the core tube) varied from a low of 227 ± 15 dpm/kg in sample 63321, 5, to a high of 360 ± 20 dpm/kg in sample 63501, 19. Sample 63321, 5 was from a scoop of soil taken from a location in the permanent shadow of a large boulder called Shadow Rock. Sample 63501, 19 was from a scoop of soil exposed to sunlight nearby.

Table 1. Ar^{37} activities and estimated solar-flare intensity within 4 months of mission.

Sample	Depth (cm)	Depth (g/cm^2)	Recovery date	Flare date	Ar^{37} (dpm/kg)*	Ca (%)	Ar^{37} (dpm/kg Ca)	ΔAr^{37}† (dpm/kg Ca)	Solar proton flux** ($1/cm^2 sr$)
60007, 93, 94, 95	0–1.5	0–2.1	21 April 1972	19 April 1972	39.0 ± 2.8	12.0	325 ± 22	89 ± 47	$(1.0 \pm 0.6) \times 10^6$
60007, 96, 97, 98	3.5–5.0	4.9–7.0	21 April 1972		47.9 ± 1.9	12.0	400 ± 16	–	–
60007, 99, 100, 101	10.0–11.5	14.0–16.1	21 April 1972		58.5 ± 2.4	12.0	487 ± 20		–
60007, 102, 103, 104	18.0–19.5	25.2–27.3	21 April 1972		68.1 ± 2.9	12.0	567 ± 24	–	–
15555, 98	0–0.7	0–2.0	2 August 1971	none	15.8 ± 2.8	6.7	236 ± 42	–	–
15555, 80	~6	~17	2 August 1971	none	31.2 ± 3.3	6.7	465 ± 49	–	–
15555, 77	~14	~40	2 August 1971	none	35.0 ± 6.5	6.7	520 ± 97	–	–
14321, 81, 83	0–0.5	0–1.5	6 February 1971	24 January 1971	38.5 ± 2.5	6.1	632 ± 40	396 ± 58 (530 ± 77)*	$(6.0 \pm 0.9) \times 10^6$
63501, 19	(scoop from surface)	~6	21 April 1972	19 April 1972	47.2 ± 2.5	11.4	–	–	–
61241, 1	(top of trench)	~5	21 April 1972	19 April 1972	43.0 ± 2.2	11.2	–	–	–
61220, 1	bottom of trench	~15	21 April 1972	19 April 1972	58.0 ± 5.5	11.6	–	–	–
63321, 5	shadow of shadow rock	–	21 April 1972	19 April 1972	43.2 ± 4.0	11.4	–	–	–

*At time of recovery.

†Solar-flare-produced Ar^{37} from Ca, $\Delta Ar^{37} = \{Ar^{37}/\%\ Ca - [Ar^{37}(15)\ \%Ca]\}$, where $Ar^{37}(15)$ is an Apollo 15 sample at same depth.

**Energy greater than 50 MeV.

Table 2. Ar^{39} activities, chemical composition, and Ar^{39} productions from target elements at 1.0 and 15 g/cm^2 depths.*

Sample	Depth (g/cm^2)	Ar^{39} (dpm/kg)	Fe (%)	Ti (%)	Ca (%)	K (%)	Fe → Ar^{39} (dpm/kg)†	Ca → Ar^{39} (dpm/kg)†	K → Ar^{39} (dpm/kg)†
60007, 93, 94, 95	0–2.1	7.5 ± 1.0	4.0	0.26	11.4	0.075	0.80 ± 0.16	6.8 ± 1.1	0.5 ± 0.2
60007, 96, 97, 98	4.9–7.0	8.6 ± 1.2	4.0	0.26	11.4	0.075	–	–	–
60007, 99, 100, 101	14.0–16.1	6.7 ± 1.0	4.0	0.26	11.4	0.075	0.80 ± 0.16	4.5 ± 1.1	1.5 ± 0.2
60007, 102, 103, 104	25.2–27.3	9.8 ± 1.5	4.0	0.26	11.4	0.075	–	–	–
15555, 98	0–2.0	8.4 ± 0.5	17.5	1.36	6.7	0.025	3.50 ± 0.7	4.0 ± 0.7	0.2 ± 0.1
15555, 80	~17	7.5 ± 0.5	17.5	1.36	6.7	0.025	3.50 ± 0.7	2.7 ± 0.7	0.5 ± 0.1
15555, 77	~40	9.8 ± 0.8	17.5	1.36	6.7	0.025	–	–	–
12002, 57	0–2.4	8.0 ± 0.7	16.5	1.5	5.4	0.045	3.30 ± 0.7	3.2 ± 0.5	0.3 ± 0.1
12002, 57	2.4–9.3	8.2 ± 0.5	16.5	1.5	5.4	0.045	–	–	–
12002, 59	14.7–19.2	7.6 ± 0.6	16.5	1.5	5.4	0.045	3.30 ± 0.7	2.2 ± 0.5	0.9 ± 0.1
14321, 81	0–1.5	8.8 ± 0.5	8.6	1.2	6.1	0.37	1.76 ± 0.4	3.7 ± 0.6	2.8 ± 0.9
14321, 81	1.5–3.0	8.3 ± 0.7	8.6	1.2	6.1	0.37	–	–	–
14321, 81	3.0–4.5	9.5 ± 0.8	8.6	1.2	6.1	0.37	–	–	–
14321, 81	~15	12.1 ± 1.0	8.6	1.2	6.1	0.37	1.76 ± 0.4	2.4 ± 0.6	7.4 ± 1.6
14321, 95	~36	14.8 ± 1.0	8.6	1.2	6.1	0.37	–	–	–
63501, 19	~6	7.7 ± 1.2	4.0	0.3	11.4	0.075	–	–	–
61241, 1	~3	6.6 ± 1.5	4.15	0.28	11.2	0.083	–	–	–
61220, 1	~15	8.0 ± 1.6	3.54	0.29	11.6	0.075	–	–	–
6321, 5	shadow of shadow rock	7.9 ± 1.0	–	–	–	–	–	–	–

*At a depth of ~1 g/cm^2, Ar^{39} productions are 20 ± 4 dpm/kg Fe, 60 ± 70 dpm/kg Ca, and 700 ± 200 dpm/kg K (see text).

†At a depth of ~15 g/cm^2, Ar^{39} productions are 21 ± 4 dpm/kg Fe, 35 ± 7 dpm/kg Ca, and 2000 ± 300 dpm/kg K (see text).

Table 3. H^3 activities versus depth in Apollo 16.

Sample	Depth (g/cm^2)	H^3 (dpm/kg)
60007, 93, 945	0-2.1	430 ± 25
60007, 96, 97, 98	4.9-7.0	300 ± 20
60007, 99, 100, 101	14.0-16.1	250 ± 15
60007, 102, 103, 104	25.2-27.3	280 ± 20
63501, 19	~6	*360 ± 20*
61241, 1	~5	280 ± 30
61220, 1	~15	266 ± 15
6321, 5	shadow of shadow rock	227 ± 15

REFERENCES

BEGEMANN, F., VILCSEK, E., RIEDER, R., BORN, W., and WÄNKE, H.
1970. Cosmic-ray produced radioisotopes in lunar samples from the Sea of Tranquility. Proc. Apollo 11 Lunar Science Conference, Geochim. Cosmochim. Acta Suppl. 1, vol. 2, pp. 995-1007.

BOCHSLER, P., WAHLEN, M., EBERHARDT, P., GEISS, J., and OESCHGER, H.
1971. Tritium measurements of lunar material (fines 10084 and breccia 10046) from Apollo 11, 1971. Proc. Second Lunar Science Conference, Geochim. Cosmochim. Acta Suppl. 2, vol. 2, pp. 1803-1812.

D'AMICO, J., DeFELICE, J., and FIREMAN, E. L.
1970. The cosmic-ray and solar flare bombardment of the moon. Proc. Apollo 11 Lunar Science Conference, Geochim. Cosmochim. Acta Suppl. 1, vol. 2, pp. 1029-1036.

D'AMICO, J., DeFELICE, J., FIREMAN, E. L., JONES, C., and SPANNAGEL, G.
1971. Tritium and argon radioactivities and their depth variations in Apollo 12 samples. Proc. Second Lunar Science Conference, Geochim. Cosmochim. Acta Suppl. 2, vol. 2, pp. 1825-1839.

FIREMAN, E. L., D'AMICO, J., and DeFELICE, J.
1970. Tritium and argon radioactivities in lunar material. Science, vol. 167, pp. 566-568.

FIREMAN, E. L., D'AMICO, J., DeFELICE, J., and SPANNAGEL, G.
1972. Radioactivities in returned lunar material. Proc. Third Lunar Science Conference, vol. 2 (in press).

MORE, K., and TIFFANY, O. L.
1962. Comparison of Monte Carlo and ionization calculations for spacecraft shielding. In Proc. Symposium on Protection against Radiation Hazards, Oak Ridge National Laboratory, TID 7652, 682 ff.

REEDY, R. C., and ARNOLD, J. R.
1972. Interaction of solar and galactic cosmic-ray particles with the moon. Journ. Geophys. Res., vol. 77, pp. 537-555.

STOENNER, R. W., LYMAN, W. J., and DAVIS, R., Jr.

1970a. Cosmic-ray production of rare gas radioactivities and tritium in lunar material. Science, vol. 167, pp. 553-555.

1970b. Cosmic-ray production of rare gas radioactivities and tritium in lunar material. Proc. Apollo 11 Lunar Science Conference, Geochim. Cosmochim. Acta Suppl. 1, vol. 2, pp. 1029-1036.